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PROPERTIES OF ENGINEERING MATERIALS FOR USE IN ROTATING MACHINERY AT CRYOGENIC TEMPERATURES
pt.2

William Martin Dubbs

[PT. 2]

PROPERTIES OF ENGINEERING MATERIALS FOR USE IN ROTATING MACHINERY AT CRYOGENIC TEMPERATURES

by

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1967

Submitted in Partial Fulfillment of the Requirements

for the Degree of Ocean Engineer and the Degree of

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1974

Thesis
D 7833
pt 2

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
Commercially Pure Ti[8]	30 (RT)	30 (20°K)	51 (RT)	56 (20°K)
Commercial Grade Ti[7], RS-70 sheet, annealed	35 (RT)	14 (20°K)	NO DATA	NO DATA
Ti-5Al-2.5Sn[5,8], sheet, annealed	15 (RT)	6 (20°K)	28 (RT)	9 (20°K)
Ti-5Al-2.5Sn[5], bar	13 (RT)	3 (20°K)	28 (RT)	9 (20°K)
Ti-5Al-2.5Sn[8], normal interstitial	17 (RT)	5 (20°K)	NO DATA	NO DATA
Ti-5Al-2.5Sn[8], extra low interstitial	17 (RT)	12 (20°K)	NO DATA	NO DATA
Ti-5Al-2.5Sn[8], annealed, normal interstitial	NO DATA	NO DATA	44 (RT)	18 (20°K)
Ti-5Al-4Zr-1V[5], sheet, annealed	16 (RT)	4.5 (20°K)	NO DATA	NO DATA
Ti-5Al-5Zr-5Sn[5], sheet, annealed	17 (RT)	10 (20°K)	NO DATA	NO DATA
Ti-7Al-12Zr[6,8], sheet, annealed	13 (RT)	5.5 (20°K)	NO DATA	NO DATA

Table 4.21 Percentage Elongation and Percentage Reduction in Area of Titanium and Titanium Alloys

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
Ti-8Al-2Cb-1Ta[5,8], sheet	13 (RT)	1 (20°K)	NO DATA	NO DATA
Ti-8Al-2Cb-1Ta[8], sheet, annealed	5 (RT)	1.5 (20°K)	NO DATA	NO DATA
Ti-8Al-1Mo-1V[8], sheet, annealed	16 (RT)	2.5 (20°K)	NO DATA	NO DATA
Ti-8Al-1Mo-1V[8], sheet, duplex annealed	16 (RT)	2 (20°K)	NO DATA	NO DATA
TITANIUM-ALPHA BETA				
Ti-4Al-3Mo-1V[5], sheet, soln treated, aged	8.2 (RT)	1.5 (20°K)	NO DATA	NO DATA
Ti-5Al-4V[7], sheet, annealed	13 (RT)	2 (20°K)	NO DATA	NO DATA
Ti-6Al-4V[5,8], sheet, annealed	14 (RT)	1.5 (20°K)	NO DATA	NO DATA
Ti-6Al-4V[5], bar	14 (RT)	2 (20°K)	46 (RT)	3 (20°K)
Ti-6Al-4V[8], annealed, normal interstitial	12 (RT)	3 (20°K)	48 (RT)	31 (20°K)

Table 4.21 Percentage Elongation and Percentage Reduction in Area of Titanium and Titanium Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
Ti-6Al-4V[8], extra low interstitial	12.5 (RT)	5 (20°K)	NO DATA	NO DATA
Ti-6Al-6V-2Sn[8], annealed	18 (RT)	10 (4.2°K)	40 (RT)	26 (4.2°K)
Ti-6Al-6V-2Sn[8], soln treated, aged	8 (RT)	3 (4.2°K)	18 (RT)	20 (4.2°K)
TITANIUM-BETA				
Ti-13V-11Cr-3Al[7], sheet, cold rolled, annealed	28 (RT)	0 (20°K)	NO DATA	NO DATA
Ti-13V-11Cr-3Al[8], soln treated	27 (RT)	0 (20°K)	56 (RT)	3 (20°K)

Table 4.21 Percentage Elongation and Percentage Reduction in Area of Titanium and Titanium Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
MAGNESIUM ALLOYS				
AZ31B-0[5,7,20], wrought sheet	25.5 (RT)	7 (20°K)	NO DATA	NO DATA
ZE10A-H11[5,20], sheet, cold worked	29.5 (RT)	11 (20°K)	NO DATA	NO DATA
HM31A-F[5,7,20], extruded	9.5 (RT)	11 (20°K)	NO DATA	NO DATA
HM21A-T8[5,7,20], wrought sheet	8 (RT)	8 (20°K)	NO DATA	NO DATA
HK31A-T6[5,7,20], sand cast	10 (RT)	4.5 (20°K)	NO DATA	NO DATA
HK-31A-0[5,7,20], wrought sheet	36 (RT)	11 (20°K)	NO DATA	NO DATA
ZK60A-T5[7], extruded	26 (RT)	3 (20°K)	NO DATA	NO DATA
COBALT ALLOYS				
Haynes 25[5], sheet 20% cold rolled	16.5 (RT)	19 (20°K)	NO DATA	NO DATA
Haynes 25[5], sheet 40% cold rolled	3 (RT)	1 (20°K)	NO DATA	NO DATA

Table 4.22 Percentage Elongation and Percentage Reduction in Area of Miscellaneous Metals

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
Elgiloy[8], bar, 45% cold red	11 (RT)	7 (20°K)	47 (RT)	31 (20°K)
OTHERS				
Tantalum[5], bar, wrought, stress relieved	28 (RT)	NO DATA	96 (RT)	90 (20°K)
Tantalum[5], bar, recrystallized	65 (RT)	28 (20°K)	98 (RT)	86 (20°K)
Columbium[5], bar, wrought, stress relieved relieved	32 (RT)	3 (20°K)	96 (RT)	9 (20°K)
Columbium[5], bar, recrystallized	60 (RT)	2 (20°K)	94 (RT)	28 (20°K)
Commercially Pure Lead[7] cast	30 (RT)	37 (20°K)	NO DATA	NO DATA

Table 4.22 Percentage Elongation and Percentage Reduction in Area of Miscellaneous Metals (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
TFE Teflon[8], sheet, 25% Asbestos filled	15 (RT)	0 (20°K)	NO DATA	NO DATA
FEP Teflon[8], 20% glass filled	40 (RT)	0 (20°K)	NO DATA	NO DATA
TFE Teflon[8], sheet, 116 glass cloth	20 (RT)	2 (20°K)	NO DATA	NO DATA
FEP Teflon[8], sheet, 116 glass cloth	16 (RT)	2 (20°K)	NO DATA	NO DATA
EPOXY-FIBERGLASS LAMINATE-S/901 ROVING REINFORCEMENT-PANELS				
E-787 Resin[8], unidirectional filament, parallel to reinf.	4.4 (RT)	5.1 (20°K)	NO DATA	NO DATA
E-787 Resin[8], 1543 cloth reinf., parallel to reinf.	3.6 (RT)	5.6 (20°K)	NO DATA	NO DATA
E-787 Resin[8], bidirectional reinf., parallel to reinf.	3.5 (RT)	4.1 (20°K)	NO DATA	NO DATA
DER-332/BF_3 Resin[8], bidirectional filament	3.5 (RT)	3.9 (20°K)	NO DATA	NO DATA

Table 4.23 Percentage Elongation and Percentage Reduction in Area of Composite Materials

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
DER-332/DEH 50 Resin[8], bidirectional filament	3.4 (RT)	4 (20°K)	NO DATA	NO DATA
POLYESTER-FIBERGLASS LAMINATE				
Selectron 5158 Resin[8], S/901 roving bidirectional filament, parallel to reinf.	3 (RT)	3.5 (20°K)	NO DATA	NO DATA

Talbe 4.23 Percentage Elongation and Percentage Reduction in Area of Composite Materials (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
Mylar[8], 15% crystallinity	97 (RT)	8 (20°K)	NO DATA	NO DATA
Mylar[8], 55% crystallinity	102 (RT)	0 (20°K)	NO DATA	NO DATA
TFE Teflon[8], 49-66% crystallinity	175 (RT)	0 (20°K)	NO DATA	NO DATA
FEP Teflon[8], 44-49% crystallinity	365 (RT)	2 (20°K)	NO DATA	NO DATA
KEL-F[8], sheet, 40-70% crystallinity	140 (RT)	1 (20°K)	NO DATA	NO DATA
KEL-F[8], type 81, sheet, 40-65% crystallinity	140 (RT)	5 (20°K)	NO DATA	NO DATA
DER-332/DEH 50 resin[8],	5 (RT)	1.1 (20°K)	NO DATA	NO DATA
E-787 resin[8]	2 (RT)	0.7 (20°K)	No DATA	NO DATA
DER-332/BF_3 resin[8]	1.5 (RT)	0.8 (20°K)	NO DATA	NO DATA

Table 4.24 Percentage Elongation and Percentage Reduction in Area of Polymers

MATERIAL	ν (upper temp)	ν (lowest temp)
Pure Aluminum[5]	0.347 (RT)	0.331 (4.2°K)
AISI/SAE 4340 Steel[5] annealed	0.287 (RT)	0.268 (4.2°K)
AISI 301 Stainless[5] Steel	0.307 (RT)	0.292 (20°K)
Pure Ti[5,8]	0.338 (RT)	0.305 (4.2°K)
Ti-6Al-4V[8], extra low interstitial	0.323 (RT)	0.297 (20°K)
Ti-7Mn[5]	0.313 (RT)	0.302 (4.2°K)
Pure Magnesium[5]	0.308 (RT)	0.295 (4.2°K)

Table 4.25 Poisson's Ratio of Various Materials

MATERIAL	τ_{uts} (upper temp)	τ_{uts} (lowest temp)
2014-T6[8], sheet, longitudinal	45000 (RT)	60000 (20°K)
2014-T6[8], sheet, transverse	44000 (RT)	61000 (20°K)
2219-T6[8], sheet, longitudinal	37000 (RT)	62000 (20°K)
2219-T6[8], sheet, transverse	42000 (RT)	64000 (20°K)
2219-T81[8], sheet	42000 (RT)	58000 (20°K)
2219-T87[8], sheet	43000 (RT)	65000 (20°K)
6061-T6[8], sheet	32000 (RT)	52000 (20°K)
7039-T6[8], sheet longitudinal	40000 (RT)	54000 (20°K)
7039-T6[8], sheet, transverse	40000 (RT)	48000 (20°K)
Inconel X[8], sheet, soln treated, aged, longitudinal	112000 (RT)	147000 (20°K)
Inconel X[8], sheet, soln treated, aged, transverse	115000 (RT)	142000 (20°K)
D-979[8], sheet, annealed	102000 (RT)	125000 (20°K)
E-787 Resin[8], S/901 cloth reinf.	8000 (RT)	10000 (20°K)
E-787 Resin[8], S/901 1543 cloth reinf.	8000 (RT)	10300 (20°K)
E-787 Resin[8], S/901 cloth reinf., unidirectional filament	8000 (RT)	8900 (20°K)

Table 4.26 Shear Strength of Various Materials in PSI

MATERIAL	τ_{uts} (upper temp)	τ_{uts} (lowest temp)
E-787 Resin[8], S/901 cloth reinf., bidirectional filament	5300 (RT)	6700 (20°K)
DER 332/DEH 50 Resin[8] S/901 cloth reinf., bidirectional filament	5000 (RT)	9300 (20°K)
DER 332/BF_3 Resin[8] S/901 cloth reinf., bidirectional filament	3200 (RT)	4600 (20°K)
Selectron 5158 Resin[8] S/901 cloth reinf., bidirectional filament	3300 (RT)	3300 (20°K)

Table 4.26 Shear Strength of Various Materials in PSI (cont.)

MATERIAL	G (upper temp)	G (lowest temp)
Pure Aluminum[5]	3.8×10^6 (RT)	4.3×10^6 (4.2°K)
AISI/SAE 4340 Steel[5] annealed	11.5×10^6 (RT)	12.5×10^6 (4.2°K)
AISI 301 Stainless[5] Steel	11.4×10^6 (RT)	12.5×10^6 (4.2°K)
Ti-6Al-4V[5], Titanium Alloy	6.1×10^6 (RT)	6.9×10^6 (4.2°K)
Ti-7Mn[5], Titanium Alloy	6.1×10^6 (RT)	6.9×10^6 (4.2°K)
Pure Titanium[5]	5.7×10^6 (RT)	6.6×10^6 (4.2°K)
Pure Magnesium[5]	2.4×10^6 (RT)	2.7×10^6 (4.2°K)
Pure Molybdenum[5]	16.5×10^6 (RT)	17.2×10^6 (4.2°K)

Table 4.27 Modulus of Ridigidy of Various Materials in PSI

MATERIAL	Impact Energy (upper temp)		Impact Energy (lowest temp)	
1100-0[7,8], bar, (Izod)	19	(RT)	25	(80°K)
1100[17], 3/4 hard, (Charpy k-notch)	27	(RT)	36	(20°K)
1100-H14[7,8], bar, (Charpy v-notch)	71	(RT)	75	(20°K)
1100-H16[7,8], bar, (Charpy k-notch)	29	(RT)	38	(20°K)
2014-T6[8], plate, (Charpy v-notch)	2.5	(RT)	4	(20°K)
2020-T6[8], bar, (Charpy v-notch)	1.5	(RT)	15	(77.6°K)
2024-T4[7,8], bar, (Charpy v-notch)	9.5	(RT)	7	(20°K)
2024-T86[8], bar, (Charpy v-notch)	3.5	(RT)	3.5	(20°K)
3003-H12[7], bar, (Charpy k-notch)	17	(RT)	22	(75°K)
5052-F[7], plate, (Charpy v-notch)	100	(RT)	48	(20°K)
5086-0[7,19], (Charpy v-notch)	13.5	(RT)	10.7	(20°K)
5154-0[7], (Charpy v-notch)	98	(RT)	53	(20°K)
5456-H343[8], plate, (unspecified), longitudinal	9.5	(RT)	7.5	(20°K)
5456-H343[8], plate, (unspecified), transverse	6	(RT)	5	(20°K)
6053-T6[7], bar, (Charpy k-notch)	80	(RT)	80	(75°K)

Table 4.28 Impact Energy of Aluminum and Aluminum Alloys in Foot-Pounds

MATERIAL	Impact Energy (upper temp)	Impact Energy (lowest temp)
6061-T[17], (Charpy k-notch)	10 (RT)	12 (20°K)
6061-T6[7], bar, (Charpy k-notch)	9 (RT)	12 (20°K)
6061-T6[8], plate, (Charpy v-notch), longitudinal	12.5 (RT)	13 (20°K)
6061-T6[8], plate, (Charpy v-notch), transverse	9 (RT)	10 (20°K)
7039-T6[8], plate, (Charpy v-notch), longitudinal	7.5 (RT)	7.5 (20°K)
7039-T6[8], plate, (Charpy v-notch), transverse	6 (RT)	4 (20°K)
7039-T61[8], plate, (Charpy v-notch), longitudinal	13 (RT)	9 (20°K)
7039-T61[8], plate (Charpy v-notch), transverse	8 (RT)	6 (20°K)
7075-T[17], (Charpy k-notch)	5 (RT)	5 (20°K)
7075-T6[7,8], rod, (Charpy v-notch)	5.5 (RT)	4 (20°K)
7075-T6[7,8], rod, (Charpy k-notch)	4 (RT)	5 (20°K)
7075-T6[7], extrusions (Izod)	7 (RT)	NO DATA

Table 4.28 Impact Energy of Aluminum and Aluminum Alloys in Foot-Pounds (cont.)

MATERIAL	Impact Energy (upper temp)	Impact Energy (lowest temp)
7079-T6[7], forged, (Charpy v-notch)	4 (RT)	3 (20°K)
195-T6[7], sand cast, (Charpy k-notch)	2 (RT)	2 (75°K)
356-T6[7], sand cast, (Charpy k-notch)	1 (RT)	1 (75°K)

Table 4.28 Impact Energy of Aluminum and Aluminum Alloys in Foot-Pounds (cont.)

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
2014-T6[8], sheet, (k_t=3.5)	75500 (RT)	101000 (20°K)
2014-T6[8], sheet, (k_t=3.8)	77000 (RT)	103000 (20°K)
2014-T6[8], sheet, (k_t=7.2)	76000 (RT)	84000 (20°K)
2014-T6[8], sheet, (k_t=8)	70000 (RT)	82000 (20°K)
2014-T6[8], sheet, (k_t=13)	63000 (RT)	73000 (20°K)
2014-T6[8], sheet, (k_t=21)	63500 (RT)	70000 (20°K)
2014-T651[8], plate, (k_t=16)	83000 (RT)	102000 (20°K)
2219-T62[8], sheet, (k_t=3.5), longitudinal	63000 (RT)	92000 (20°K)
2219-T62[8], sheet, (k_t=3.5), transverse	67000 (RT)	88000 (20°K)
2219-T62[8], sheet, (k_t=8), longitudinal	57000 (RT)	73000 (20°K)
2219-T62[8], sheet, (k_t=8), transverse	57000 (RT)	74000 (20°K)
2219-T62[8], sheet, (k_t=21), longitudinal	47000 (RT)	67000 (20°K)
2219-T62[8], sheet, (k_t=21), transverse	47000 (RT)	58000 (20°K)
2219-T851[8], plate (k_t=16)	84000 (RT)	106000 (4.2°K)

Table 4.29 Notched Tensile Strength of Aluminum and Aluminum Alloys in PSI

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
2618-T6[8], sheet, (k_t=3.5), longitudinal	64000 (RT)	89000 (20°K)
2618-T6[8], sheet, (k_t=3.5), transverse	63000 (RT)	85000 (20°K)
2618-T6[8], sheet, (k_t=8), longitudinal	60000 (RT)	75000 (20°K)
2618-T6[8], sheet, (k_t=8), transverse	57000 (RT)	71000 (20°K)
2618-T6[8], sheet, (k_t=13), longitudinal	57000 (RT)	71000 (20°K)
2618-T6[8], sheet, (k_t=13), transverse	55000 (RT)	67000 (20°K)
2618-T62[8], sheet, (k_t=3.5), longitudinal	64000 (RT)	88000 (20°K)
2618-T62[8], sheet, (k_t=3.5), transverse	64000 (RT)	85000 (20°K)
2618-T62[8], sheet, (k_t=8), longitudinal	59000 (RT)	71000 (20°K)
2618-T62[8], sheet, (k_t=8), transverse	57000 (RT)	69000 (20°K)
2618-T651[8], plate (k_t=16)	82000 (RT)	98000 (4.2°K)
5052-H38[8], sheet, (k_t=7.2), longitudinal	46500 (RT)	77500 (20°K)
5052-H38[8], sheet, (k_t=7.2), transverse	50000 (RT)	79000 (20°K)
5083-0[8,24], plate, (k_t=14)	50500 (RT)	63000 (4.2°K)

Table 4.29 Notched Tensile Strength of Aluminum and Aluminum Alloys in PSI (cont.)

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
5083-H39[8], sheet, (k_t=7.2), longitudinal	69000 (RT)	91000 (20°K)
5083-H39[8], sheet, (k_t=7.2), transverse	77000 (RT)	96000 (20°K)
5083-H113[8,24], plate, (k_t=14)	62000 (RT)	73500 (4.2°K)
5086-0[24], plate, (k_t=14)	47000 (RT)	60000 (20°K)
5086-H34[8], sheet, (k_t=7.2), longitudinal	48000 (RT)	72000 (20°K)
5086-H34[8], sheet, (k_t=7.2), transverse	47000 (RT)	58000 (20°K)
5086-H34[8], sheet, (k_t=10)	47000 (RT)	65000 (20°K)
5086-H34[8], sheet, (k_t=11)	89000 (RT)	86000 (20°K)
5086-H34[24], plate, (k_t=14)	63000 (RT)	73000 (20°K)
5154-H38[8], sheet (k_t=7.2), longitudinal	49000 (RT)	77500 (20°K)
5154-H38[8], sheet, (k_t=7.2), transverse	54000 (RT)	77500 (20°K)
5456-0[24], plate (k_t=14)	50000 (RT)	60000 (20°K)
5456-H321[24], plate, (k_t=14)	59000 (RT)	71000 (20°K)
6061-T6[8], sheet, (k_t not given)	48000 (RT)	70000 (20°K)

Table 4.29 Notched Tensile Strength of Aluminum and Aluminum Alloys in PSI (cont.)

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
6061-T651[8], plate, (k_t not given), longitudinal	69000 (RT)	90000 (4.2°K)
6061=T651[8], plate, (k_t not given), transverse	68000 (RT)	87000 (4.2°K)
7002-T6[8], plate, (k_t=7.2), longitudinal	92000 (RT)	103000 (20°K)
7002-T6[8], plate, (k_t=7.2), transverse	87000 (RT)	97000 (20°K)
7002-T6[8], plate, (k_t=13), longitudinal	70000 (RT)	89000 (20°K)
7002-T6[8], plate, (k_t=13), transverse	70000 (RT)	81000 (20°K)
7039-T6[8], sheet, (k_t=3.5), longitudinal	69000 (RT)	94000 (20°K)
7039-T6[8], sheet, (k_t=3.5), transverse	71000 (RT)	92000 (20°K)
7039-T6[8], sheet, (k_t=8), longitudinal	66000 (RT)	79000 (20°K)
7039-T6[8], sheet, (k_t=8), transverse	63000 (RT)	69000 (20°K)
7075-T6[8], sheet, (k_t=7.2), longitudinal	76000 (RT)	87000 (20°K)
7075-T6[8], sheet, (k_t=7.2), transverse	75000 (RT)	82000 (20°K)
7079-T6[8], sheet, (k_t=7.2), longitudinal	84000 (RT)	78000 (20°K)

Table 4.29 Notched Tensile Strength of Aluminum and Aluminum Alloys in PSI (cont.)

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
7079-T6[8], sheet, (k_t=7.2), transverse	82000 (RT)	77000 (20°K)
7079-T6[8], sheet, (k_t=21), longitudinal	71000 (RT)	59000 (20°K)
7079-T6[8], sheet, (k_t=21), transverse	62000 (RT)	43000 (20°K)
7079-T6[8], billet, (k_t=7.2), longitudinal	94000 (RT)	65000 (20°K)
7079-T6[8], billet, (k_t=7.2), transverse	89000 (RT)	55000 (20°K)
7178-T6[8], sheet, (k_t=7.2), longitudinal	92000 (RT)	62000 (20°K)
7178-T6[8], sheet, (k_t=7.2), transverse	84000 (RT)	56000 (20°K)
7178-T6[8], sheet, (k_t=21), longitudinal	47000 (RT)	32000 (20°K)
7178-T6[8], sheet, (k_t=21), transverse	52000 (RT)	32000 (20°K)
7178-T6[8], plate, (k_t=10)	64000 (RT)	38000 (20°K)
354-T62[25], plate, (k_t>16), permanent mold cast	54200 (RT)	57200 (20°K)
356-T61[8], cast, (k_t=16)	42000 (RT)	62000 (4.2°K)
356-T62[25], plate, (k_t>16), permanent mold cast	46200 (RT)	63300 (20°K)
B-218-F[25], sand cast, (k_t>16)	43800 (RT)	20000 (20°K)

Table 4.29 Notched Tensile Strength of Aluminum and Aluminum Alloys in PSI (cont.)

MATERIAL	IMPACT ENERGY (upper temp)	IMPACT ENERGY (lowest temp)
PURE COPPER		
Pure Copper[22], annealed (Charpy v-notch)	61 (RT)	72 (20°K)
Pure Copper[22], aged, (Charpy v-notch)	90 (RT)	115 (20°K)
Pure Copper[22], 60% cold drawn, (Charpy v-notch)	95 (RT)	83 (20°K)
OFHC Copper[7], annealed, (Charpy k-notch)	57 (RT)	72 (20°K)
OFHC Copper[7], annealed, (Izod)	42 (RT)	50 (90°K)
OFHC Copper[8], 60% cold reduced, (Charpy v-notch)	95 (RT)	83 (20°K)
OFHC Copper[18], (Charpy key-hole)	56 (RT)	72 (20°K)
COPPER-ZINC ALLOYS (BRASS)		
Commercial Bronze[8,22] 90Cu,10Zn, annealed, (Charpy v-notch)	115 (RT)	117 (20°K)
Red Brass[8], 84.7Cu,15.3Zn, 14% cold reduced, (Charpy v-notch)	96 (RT)	76 (20°K)
Admiralty Brass[8], 72.5Cu,27.5An, annealed, (Charpy v-notch)	107 (RT)	109 (20°K)

Table 4.30 Impact Energy of Copper and Copper Alloys in Foot-Pounds

MATERIAL	IMPACT ENERGY (upper temp)	IMPACT ENERGY (lowest temp)
60Cu,39Zn,1Sn[22], annealed, (Charpy v-notch)	37 (RT)	35 (20°K)
Naval Brass[8], 60.3Cu,39.7Zn, annealed, (Charpy v-notch)	38 (RT)	30 (20°K)
COPPER-TIN ALLOYS (BRONZE)		
Aluminum Bronze D[8], annealed, (Charpy v-notch)	110 (RT)	66 (20°K)
Nickel Aluminum Bronze, sand cast, (Charpy v-notch)[8]	10 (RT)	6 (20°K)
Phosphor Bronze A[8,22] 85% cold drawn, (Charpy v-notch)	106 (RT)	51 (20°K)
Phosphor Bronze D[22], 37% cold drawn, (Charpy v-notch)	50 (RT)	20 (20°K)
COPPER SILICON ALLOYS		
Silicon Bronze A[8], annealed, (Charpy v-notch)	112 (RT)	117 (20°K)
Silicon Bronze[22], hard, (Charpy v-notch)	73 (RT)	52 (20°K)
COPPER-NICKEL ALLOYS		
Copper Nickel 10[8,22] annealed, (Charpy v-notch)	114.5 (RT)	115.5 (20°K)

Table 4.30 Impact Energy of Copper and Copper Alloys in Foot-Pounds (cont.)

MATERIAL	IMPACT ENERGY (upper temp)	IMPACT ENERGY (lowest temp)
Copper Nickel 30[8,22] annealed, (Charpy v-notch)	115 (RT)	115 (20°K)
Copper-Nickel-Silicon[8], aged, (not specified)	110 (RT)	116 (20°K)
COPPER-BERYLLIUM ALLOYS		
Beryllium Copper[7], wrought, cold drawn, 1/2 hard, 97.7Cu,2Be, 0.3Co, (Charpy v-notch)	72 (RT)	55 (20°K)
Beryllium Copper[7], wrought, cold drawn, 1/2 hard, age hardened, 97.7Cu,2Be,0.3Co, (Charpy k-notch)	7 (RT)	8 (90°K)
Beryllium Copper[7], wrought, soln treated, 97.7Cu, 2Be, 0.3Co, (Charpy k-notch)	105 (RT)	75 (90°K)
Beryllium Copper[7], cast, soln treated, age hardened, 97.4Cu, 2Be, 0.6Co, (Charpy k-notch)	2 (RT)	2 (90°K)
Beryllium Copper[8], 1/2 hard, (Charpy v-notch)	72 (RT)	50 (20°K)

Table 4.30 Impact Energy of Copper and Copper Alloys in Foot-Pounds (cont.)

MATERIAL	IMPACT ENERGY (upper temp)	IMPACT ENERGY (lowest temp)
Beryllium Cobalt[7] Bronze, wrought, cold drawn to 1/2 hard, 96.8Cu, 2.6Co, 0.6Be, (Charpy v-notch)	23 (RT)	24 (20°K)
Beryllium Cobalt[7] Bronze, cast, soln treated, aged hardened, 96.8Cu,2.6Co,0.6Be, (Charpy k-notch)	10 (RT)	12 (90°K)
Beryllium Zinc[7] Bronze, wrought, cold drawn, 1/4 hard, age hardened, 98Cu, 1.1Be,0.9Zn, (Charpy k-notch)	12 (RT)	12 (90°K)

Table 4.30 Impact Energy of Copper and Copper Alloys in Foot-Pounds (cont.)

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
COPPER-ZINC ALLOYS (BRASS)		
Commercial Bronze[8,22] 90Cu, 10Zn, (k_t=4.7)	50000 (RT)	79000 (4.2°K)
Red Brass[8], 84.7Cu, 15.3Zn, 19% cold reduced, (k_t=4.7)	54000 (RT)	74000 (4.2°K)
Admiralty Brass[8], 72.5Cu, 27.5Zn, annealed, (k_t=4.7)	54000 (RT)	86000 (4.2°K)
Naval Brass[8], 60.3Cu, 39.7Zn, annealed, (k_t=4.7)	75000 (RT)	115000 (4.2°K)
COPPER-TIN ALLOYS (BRONZE)		
Aluminum Bronze D[8], annealed, (k_t=4.7)	122000 (RT)	160000 (4.2°K)
Nickel Aluminum Bronze[8], sand cast, (k_t=4.7)	105000 (RT)	119000 (4.2°K)
Phosphor Bronze A[8,22], 85% cold drawn, (k_t=4.7)	135000 (RT)	185000 (4.2°K)
Silicon Bronze A[8], annealed, (k_t=4.7)	80000 (RT)	121000 (4.2°K)
COPPER-NICKEL ALLOYS		
Copper Nickel 10[8,22], annealed, (k_t=4.7)	65000 (RT)	100000 (4.2°K)
Copper Nickel 30[8,22], annealed, (k_t=4.7)	80000 (RT)	130000 (4.2°K)
Copper-Nickel-Silicon[8], aged, (k_t=4.7)	190000 (RT)	215000 (4.2°K)

Table 4.31 Notched Tensile Strength of Copper and Copper Alloys in PSI

MATERIAL	Impact Energy (upper temp)	Impact Energy (lowest temp)
Commercially Pure Nickel[7], annealed, (Charpy v-notch)	215 (RT)	235 (75°K)
Commercially Pure Nickel[7], annealed, (Izod)	90 (RT)	100 (90°K)
Commercially Pure Nickel[7], cold drawn, (Charpy v-notch)	185 (RT)	212 (80°K)
Commercially Pure Nickel[7], hot rolled, (Charpy v-notch)	195 (RT)	230 (80°K)
Commercially Pure Nickel[7], as cast, (not specified)	35 (RT)	38 (78°K)
Hastelloy B[7], (Charpy u-notch)	38 (RT)	33 (20°K)
Hastelloy C[7,18], (Charpy v-notch)	56 (RT)	44 (20°K)
Hastelloy X[8], (Charpy v-notch)	76 (RT)	38 (20°K)
Inconel 718[8], forging, annealed, aged, longitudinal, (Charpy v-notch)	50 (RT)	43 (20°K)
Inconel 718[8], forging, annealed, aged, transverse, (Charpy v-notch)	20 (RT)	25 (20°K)
René 41[8], bar, soln treated, (Charpy v-notch)	15 (RT)	11 (20°K)
AL-718[6], bar, double annealed, (Charpy v-notch)	29 (RT)	25 (20°K)
L-605[8], soln treated, (Charpy v-notch)	55 (RT)	35 (20°K)

Table 4.32 Impact Energy of Nickel and Nickel Alloys in Foot-Pounds

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
Hastelloy B[8], sheet 20% cold reduced, (k_t=7.2)	155000 (RT)	210000 (20°K)
Hastelloy B[8], sheet, 40% cold reduced, (k_t=7.2)	230000 (RT)	300000 (20°K)
Hastelloy C[8], sheet, 20% cold reduced, (k_t=7.2)	182000 (RT)	245000 (20°K)
Hastelloy C[8], sheet, 20% cold reduced, aged, (k_t=7.2)	172000 (RT)	232000 (20°K)
Hastelloy C[8], sheet, soln treated, (k_t=7.2)	105000 (RT)	155000 (20°K)
Inconel 718[8], sheet, annealed and aged, (k_t=7), longitudinal	205000 (RT)	255000 (20°K)
Inconel 718[8], sheet, annealed and aged, (k_t=7), transverse	205000 (RT)	250000 (20°K)
Inconel 718[8], sheet, cold reduced, aged, (k_t=7.2)	250000 (RT)	300000 (20°K)
Inconel X[8], sheet, soln treated, aged, (k_t=7)	172000 (RT)	200000 (20°K)
K-Monel[8], sheet, soln treated, aged (k_t=10)	90000 (RT)	130000 (20°K)
René 41[8], sheet, soln treated, (k_t=7.2)	168000 (RT)	219000 (20°K)
René 41[8], sheet, soln treated, (k_t=10)	180000 (RT)	197000 (20°K)
René 41[8], sheet, soln treated, (k_t=21)	147000 (RT)	172000 (20°K)

Table 4.33 Notched Tensile Strength of Nickel and Nickel Alloys in PSI

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
AL-718[6], forging annealed, (k_t=6.3)	271000 (RT)	308000 (20°K)
AL-718[6], strip cold rolled, (k_t=6.5)	NO DATA	316000 (20°K)
AL-718[6], strip, cold rolled, aged, (k_t=6.3)	182000 (RT)	236000 (77.6°K)
D-979[8], sheet, annealed, (k_t=3.5)	146000 (RT)	200000 (20°K)
D-979[8], sheet, annealed, (k_t=8)	130000 (RT)	169000 (20°K)
L-605[8], sheet, annealed, (k_t=8)	115000 (RT)	200000 (20°K)
L-605[8], sheet, 20% cold reduced, (k_t=7.2)	170000 (RT)	270000 (20°K)
L-605[8], sheet, 40% cold reduced, (k_t=7.2)	240000 (RT)	280000 (20°K)
R-235[8], sheet, soln treated, (k_t=7.2)	97000 (RT)	140000 (20°K)

Table 4.33 Notched Tensile Strength of Nickel and Nickel Alloys in PSI (cont.)

MATERIAL	Impact Energy (upper temp)	Impact Energy (lowest temp)
CONSTRUCTION STEEL		
AISI/SAE 1043[21], plate, (unnotched)	145 (RT)	0 (77°K)
AISI/SAE 2330[7], quenched, tempered, (Charpy k-notch)	36 (RT)	17 (20°K)
AISI/SAE 2330[7], normalized, (Charpy k-notch)	18 (RT)	3 (20°K)
AISI/SAE 2800[8], double normalized, stress relieved, (Charpy v-notch)	112 (RT)	30 (20°K)
AISI/SAE 4340[8], quenched, tempered, (Charpy v-notch)	12 (RT)	5 (20°K)
AISI/SAE 8630[7], normalized, (Charpy, k-notch)	29 (RT)	3 (20°K)
AISI/SAE 8630[7], quenched, tempered, (Charpy k-notch)	39 (RT)	5 (20°K)
9% Ni Steel[7], double normalized, stress relieved, (Charpy k-notch)	48 (RT)	21 (20°K)
9% Ni Steel[11], double normalized, tempered, (Charpy v-notch)	100 (RT)	25 (20°K)
9% Ni Steel[11], quenched tempered, (Charpy v-notch	99 (RT)	36 (20°K)
18% Ni Maraging Steel[8], soln treated, aged, (Charpy v-notch)	23 (RT)	17 (20°K)

Table 4.34 Impact Energy of Ferrous Materials in Foot-Pounds

MATERIAL	Impact Energy (upper temp)	Impact Energy (lowest temp)
INVAR[8], bar, cold reduced, (Charpy k-notch)	26 (RT)	20 (20°K)
STAINLESS STEEL-AUSTENITIC		
AISI 303[8], bar, cold reduced, (Charpy k-notch)	50 (RT)	42 (20°K)
AISI 304[7], annealed, (Charpy k-notch)	78 (RT)	80 (20°K)
AISI 304[7], cold drawn to 210000 UTS, (Charpy k-notch)	26 (RT)	26 (20°K)
AISI 304[8], bar, cold drawn to 211000 UTS, (Charpy k-notch)	25 (RT)	25 (20°K)
AISI 304[6], plate, (Charpy v-notch)	110 (RT)	90 (20°K)
AISI 310[6], plate, (Charpy v-notch)	100 (RT)	80 (20°K)
AISI 316[6], plate, (Charpy v-notch)	110 (RT)	90 (20°K)
CAST STAINLESS STEEL		
CF-8, annealed (Charpy k-notch)	75 (RT)	52 (20°K)

Table 4.34 Impact Energy of Ferrous Materials in Foot-Pounds (cont.)

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
CONSTRUCTION STEEL		
18% Ni Maraging Steel[8], soln treated, (k_t=7.2)	180000 (RT)	330000 (20°K)
18% Ni Maraging Steel[8], soln treated, (k_t=21)	210000 (RT)	130000 (20°K)
18% Ni Maraging Steel[8], soln treated, aged, (k_t=7.2)	330000 (RT)	260000 (20°K)
STAINLESS STEEL-AUSTENITIC		
AISI 301[8], sheet, 3/4 hard, (k_t=7.2), longitudinal	200000 (RT)	248000 (20°K)
AISI 301[8], sheet, 3/4 hard, (k_t=7.2), transverse	187500 (RT)	152500 (20°K)
AISI 301[8], extra full hard, (k_t=7.2)	240000 (RT)	310000 (20°K)
AISI 304[8], sheet, extra low carbon, full hard, (k_t=3.8), longitudinal	190000 (RT)	315000 (20°K)
AISI 304[8], sheet, extra low carbon, full hard, (k_t=3.8), transverse	220000 (RT)	365000 (20°K)
AISI 304[8], sheet, extra low carbon, full hard, (k_t=7.2), longitudinal	200000 (RT)	315000 (20°K)
AISI 304[8], sheet, extra low carbon, full hard, (k_t=7.2), transverse	220000 (RT)	335000 (20°K)

Table 4.35 Notched Tensile Strength of Ferrous Materials in PSI

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
AISI 304[8], sheet, extra low carbon, full hard, (k_t=21), longitudinal	170000 (RT)	240000 (20°K)
AISI 304[8], sheet, extra low carbon, full hard, (k_t=21), transverse	144000 (RT)	208000 (20°K)
AISI 304L[6], strip cold rolled, full hard, (k_t=6.3)	192000 (RT)	302000 (20°K)
AISI 310[8], sheet, 75% cold reduced, (k_t=3.8), longitudinal	200000 (RT)	340000 (20°K)
AISI 310[8], sheet, 75% cold reduced, (k_t=3.8), transverse	215000 (RT)	385000 (20°K)
AISI 310[8], sheet, 75% cold reduced, (k_t=7.2), longitudinal	200000 (RT)	330000 (20°K)
AISI 310[8], sheet, 75% cold reduced, (k_t=7.2), transverse	200000 (RT)	330000 (20°K)
AISI 310[8], sheet, 75% cold reduced, (k_t=21), longitudinal	160000 (RT)	210000 (20°K)
AISI 310[8], sheet, 75% cold reduced, (k_t=21), transverse	120000 (RT)	190000 (20°K)
AISI 310[6], strip, cold rolled, extra hard, (k_t=6.3)	197000 (RT)	312000 (20°K)

Table 4.35 Notched Tensile Strength of Ferrous Materials in PSI (cont.)

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
AISI 347[8], plate, annealed, (k_t=6.3)	105000 (RT)	195000 (4.2°K)
A-286[8], soln treated, (k_t=3.5)	185000 (RT)	255000 (20°K)
A-286[8], soln treated, (k_t=7.2)	135000 (RT)	200000 (20°K)
A-286[8], soln treated, (k_t=10)	80000 (RT)	130000 (20°K)
AM-350[8], sub-zero cooled, tempered, (k_t=6.6)	80000 (RT)	210000 (20°K)
AM-355[8], sheet, cold rolled, tempered, (k_t=7.2), longitudinal	255000 (RT)	125000 (20°K)
AM-355[8], sheet, cold rolled, tempered, (k_t=7.2), transverse	230000 (RT)	125000 (20°K)

Table 4.35 Notched Tensile Strength of Ferrous Materials in PSI (cont.)

MATERIAL	Impact Energy (upper temp)	Impact Energy (lowest temp)
TITANIUM-ALPHA		
Commercially Pure Ti[7], annealed, (Charpy k-notch)	14 (RT)	4 (20°K)
Commercially Pure Ti[8], annealed, 40000 PSI yield, longitudinal, (Charpy v-notch)	60 (RT)	12 (20°K)
Commercially Pure Ti[8], annealed, 40000 PSI yield, transverse, (Charpy v-notch)	46 (RT)	14 (20°K)
Ti-5Al-2.5Sn[8], normal interstitial, annealed, (Charpy v-notch)	23 (RT)	8 (20°K)
TITANIUM-ALPHA-BETA		
Ti-4Al-4Mn[7], annealed, (Charpy k-notch)	10 (RT)	3 (20°K)
Ti-6Al-4V[8], soln treated, aged, (Charpy v-notch)	17 (RT)	12 (20°K)
Ti-6Al-4V[8], normal interstitial, annealed, (Charpy v-notch)	22 (RT)	8 (20°K)
Ti-6Al-4V[8], extra low interstitial, annealed, (Charpy v-notch)	18 (RT)	12 (20°K)
TITANIUM-BETA		
Ti-13V-11Cr-3Al[8], soln treated, (Charpy v-notch)	5 (RT)	3 (20°K)

Table 4.36 Impact Energy of Titanium and Titanium Alloys in Foot-Pounds

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
TITANIUM-ALPHA		
Commercially Pure Ti[8] annealed, (k_t=6.3)	150000 (RT)	235000 (20°K)
Commercially Pure Ti[8] annealed, (k_t=7.2)	100000 (RT)	160000 (20°K)
Commercially Pure Ti[8] annealed, (k_t=13.6)	75000 (RT)	125000 (20°K)
Ti-5Al-2.5Sn[5], sheet, annealed, (k_t=3)	175000 (RT)	295000 (20°K)
Ti-5Al-2.5Sn[8], sheet, annealed, extra low interstitial, (k_t=7.2)	150000 (RT)	230000 (20°K)
Ti-5Al-2.5Sn[8], sheet, annealed, extra low interstitial, (k_t=21)	115000 (RT)	120000 (20°K)
Ti-5Al-2.5Sn[8], sheet, annealed, normal interstitial, (k_t=3.5)	160000 (RT)	270000 (20°K)
Ti-5Al-2.5Sn[8], sheet, annealed, normal interstitial, (k_t=7.2)	150000 (RT)	180000 (20°K)
Ti-5Al-2.5Sn[8], sheet, annealed, normal interstitial, (k_t=21)	125000 (RT)	110000 (20°K)
Ti-7Al-12Zr[8], sheet, (k_t=7.2), longitudinal	175000 (RT)	140000 (20°K)
Ti-7Al-12Zr[8], sheet, (k_t=7.2), transverse	180000 (RT)	155000 (20°K)
Ti-8Al-1Mo-1V[8], sheet, annealed, (k_t=3.5)	175000 (RT)	280000 (20°K)
Ti-8Al-1Mo-1V[8], sheet, annealed, (k_t=7.2)	155000 (RT)	180000 (20°K)

Table 4.37 Notched Tensile Strength of Titanium and Titanium Alloys in PSI

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
Ti-8Al-1Mo-1V[8], sheet, annealed, (k_t=8)	150000 (RT)	140000 (20°K)
Ti-8Al-1Mo-1V[8], sheet, annealed, (k_t=10)	145000 (RT)	140000 (20°K)
Ti-8Al-1Mo-1V[8], sheet, duplex annealed, (k_t=3.5)	170000 (RT)	250000 (20°K)
Ti-8Al-1Mo-1V[8], sheet, duplex annealed, (k_t=8)	160000 (RT)	160000 (20°K)
Ti-8Al-2Cb-1Ta[8], sheet, annealed, (k_t=7.2), longitudinal	151000 (RT)	207000 (20°K)
Ti-8Al-2Cb-1Ta[8], sheet, annealed, (k_t=7.2), transverse	151000 (RT)	192000 (20°K)
TITANIUM-ALPHA-BETA		
Ti-6Al-4V[5], sheet, annealed, (k_t=3)	162000 (RT)	300000 (20°K)
Ti-6Al-4V[8], sheet, extra low interstitial, annealed, (k_t=3.5)	170000 (RT)	300000 (20°K)
Ti-6Al-4V[8], sheet, extra low interstitial, annealed, (k_t=7.2)	165000 (RT)	190000 (20°K)
Ti-6Al-4V[8], sheet, extra low interstitial, annealed, (k_t=8)	160000 (RT)	175000 (20°K)
Ti-6Al-4V[8], sheet, extra low interstitial, annealed, (k_t=21)	135000 (RT)	110000 (20°K)
TITANIUM-BETA		
Ti-13V-11Cr-3Al[8], sheet, soln treated, (k_t=3)	195000 (RT)	100000 (20°K)

Table 4.37 Notched Tensile Strength of Titanium and Titanium Alloys in PSI (cont.)

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
Ti-13V-11Cr-3Al[8], sheet, soln treated, (k_t=7.2)	165000 (RT)	130000 (20°K)
Ti-13V-11Cr-3Al[8], sheet, soln treated, (k_t=10)	155000 (RT)	90000 (20°K)

Table 4.37 Notched Tensile Strength of Titanium and Titanium Alloys in PSI (cont.)

MATERIAL	Impact Energy (upper temp)	Impact Energy (lowest temp)
MAGNESIUM AND MAGNESIUM ALLOYS		
Commercially Pure Magnesium[7], extruded, (Charpy k-notch)	3 (RT)	3.5 (20°K)
Commercially Pure Magnesium[7], cast, (Charpy k-notch)	3 (RT)	3 (20°K)
AZ31B-0[7,20], (Charpy v-notch)	5.9 (RT)	3 (20°K)
AZ31B[7], extruded, (Charpy k-notch)	4 (RT)	4 (20°K)
HM21A-T8[7,20], (Charpy v-notch)	1.5 (RT)	1.25 (20°K)
HK31A-01[7,20], (Charpy v-notch)	4 (RT)	3.3 (20°K)
ZK60A-T5[7], extruded (Charpy v-notch)	5 (RT)	3 (20°K)
ZE10A-H10[7,20], (Charpy v-notch)	7 (RT)	4.7 (20°K)
HM31A-F[20], (Charpy v-notch)	4.6 (RT)	4.3 (77°K)
OTHER METALS		
Commercially Pure Lead (Charpy k-notch)	12 (RT)	24 (20°K)

Table 4.38 Impact Energy of Miscellaneous Metals in Foot-Pounds

MATERIAL	Notched Tensile Strength (upper temp)	Notched Tensile Strength (lowest temp)
Tantalum[5], bar, wrought, stress relieved, (k_t=3)	95000 (RT)	293000 (20°K)
Tantalum[5], bar, recrystallized, (k_t=3)	54000 (RT)	197000 (20°K)
Columbium[5], bar, wrought, stress relieved, (k_t=3)	67000 (RT)	258000 (20°K)
Columbium[5], bar, recrystallized, (k_t=3)	46000 (RT)	136000 (20°K)

Table 4.39 Notched Tensile Strength of Miscellaneous Metals in PSI

MATERIAL	Impact Energy (upper temp)	Impact Energy (lowest temp)
COMPOSITE MATERIALS		
TFE Teflon[8], sheet, 15% graphite filled, (Izod)	2.2 (RT)	1 (20°K)
TFE Teflon[8], sheet, 65% bronze filled, (Izod)	2 (RT)	1.25 (20°K)
TFE Teflon[8], sheet, 25% asbestos filled, (Izod)	1.5 (RT)	0.8 (20°K)
FEP Teflon[8], sheet, 116 glass cloth reinf., through fabric, (Izod)	38 (RT)	25 (20°K)
FEP Teflon[8], sheet 116 glass cloth reinf., with fabric, (Izod)	29 (RT)	18 (20°K)
TFE Teflon[8], sheet, 128 glass cloth reinf., through fabric, (Izod)	12 (RT)	11 (20°K)
TFE Teflon[8], sheet, 128 glass cloth reinf., with fabric, (Izod)	1.5 (RT)	0.5 (20°K)
POLYMERS		
Nylon[8], Type 101, sheet, (Izod)	0.5 (RT)	0.6 (20°K)
TFE Teflon[8], sheet, 52.5-71% crystallinity, (Izod)	2 (RT)	1.7 (20°K)
KEL-F[8], sheet, 60-70% crystallinity, (Izod)	1.25 (RT)	1.4 (20°K)

Table 4.40 Impact Energy of Composite Materials and Polymers in Foot-Pounds per Inch of Notch

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
1100-H16[8], bar, flexure, (17.5 ksi UTS), R=-1	10000, 4×10^6 (RT)	25000, 9.5×10^3 (RT)	22000, 3×10^6 (77.6°K)	47000, 4×10^3 (77.6°K)
2014-T6[8], sheet, axial, R=-1	15000, 5×10^6 (RT)	53000, 2×10^3 (RT)	46000, 3×10^6 (20°K)	78000, 9×10^2 (20°K)
2020-T6[8], sheet, axial, (82.6 ksi UTS), R=-1	18000, 10^7 (RT)	60000, 6×10^2 (RT)	40000, 10^7 (20°K)	75000, 1.5×10^3 (20°K)
2024-T4[8], bar, flexure, (69.6 ksi UTS), R=-1	22000, 6×10^7 (RT)	77000, 1.5×10^3 (RT)	47000, 4×10^6 (77.6°K)	100000, 10^3 (77.6°K)
2219-T62[8], sheet, axial, R=-1	18000, 6×10^6 (RT)	40000, 10^3 (RT)	36000, 2×10^6 (20°K)	67000, 6×10^2 (20°K)
5083-H113[8], plate, flexure, R=-1	17000, 10^8 (RT)	26000, 10^5 (RT)	23000, 10^7 (89°K)	35000, 10^5 (89°K)
5456-H343[8], sheet, axial, (56.5 ksi UTS), R=-1	15000, 10^7 (RT)	45000, 6×10^2 (RT)	40000, 10^7 (20°K)	60000, 3×10^3 (20°K)

Table 4.41 Fatigue Strength in PSI of Aluminum and Aluminum Alloys and Corresponding Life Cycles

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
6061-T6[8], bar, flexure, (44.2 ksi UTS), R=-1	20000, 10^8 (RT)	60000, 2×10^3 (RT)	40000, 6×10^6 (77.6°K)	80000, 4×10^3 (77.6°K)
7039-T6[8], sheet, axial, R=-1	32000, 3.2×10^6 (RT)	73000, 6×10^2 (RT)	57000, 3.2×10^6 (20°K)	98000, 4×10^2 (20°K)
7075-T6[8], sheet, axial, (78.8 ksi UTS), R=-1	12000, 10^7 (RT)	66000, 10^3 (RT)	35000, 10^7 (20°K)	80000, 10^3 (20°K)

Table 4.41 Fatigue Strength in PSI of Aluminum and Aluminum Alloys and Corresponding Life Cycles (cont.)

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
2014-T6[8], sheet, axial, R=-1, (k_t=3.5)	8000, 2 x 10^6 (RT)	36000, 6 x 10^2 (RT)	7000, 2 x 10^6 (20°K)	46000, 4 x 10^2 (20°K)
2014-T6[8], sheet, axial, R=-1, (k_t=8)	5000, 3 x 10^6 (RT)	28000, 2 x 10^3 (RT)	7000, 4 x 10^6 (20°K)	33000, 0.5 x 10^3 (20°K)
2219-T62[8], sheet, axial, R=-1, (k_t=3.5)	5000, 3 x 10^6 (RT)	45000, 8 x 10^2 (RT)	8000, 2 x 10^6 (20°K)	33000, 10^3 (20°K)
2219-T87[8], sheet, axial, (66.7 ksi UTS) R=-1, (k_t=3.5)	7000, 10^7 (RT)	32000, 5 x 10^3 (RT)	8000, 2 x 10^6 (20°K)	39000, 6 x 10^2 (20°K)
7039-T6[8], sheet, axial, R=-1, (k_t=8)	5000, 2 x 10^6 (RT)	33000, 9 x 10^2 (RT)	11000, 2 x 10^6 (20°K)	37000, 4 x 10^2 (20°K)
7075-T6[8], sheet, axial, (78.8 ksi UTS) R=-1, (k_t=3.5)	8000, 8 x 10^6 (RT)	31000, 10^3 (RT)	11000, 2 x 10^6 (20°K)	38000, 7 x 10^2 (20°K)
7075-T6[8], bar, flexure, (83.9 ksi UTS) R=-1, (k_t=3.2)	15000, 10^7 (RT)	50000, 4 x 10^3 (RT)	27000, 10^6 (20°K)	53000, 8 x 10^2 (20°K)

Table 4.42 Notch Fatigue Strength in PSI of Aluminum and Aluminum Alloys and Corresponding Life Cycles

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
PURE COPPER				
ETP Copper[8], rod, axial, annealed, R=-1	31000, 1.5×10^6 (RT)	36000, 10^4 (RT)	42500, 1.5×10^6 (4.2°K)	45000, 4×10^4 (4.2°K)
COPPER-ZINC ALLOYS (BRASS)				
70/30 Brass[8], sheet, flexure, cold rolled, stress relieved, R=1	25000, 10^7 (RT)	90000, 3×10^4 (RT)	100000, 10^6 (20°K)	175000, 10^5 (20°K)
COPPER-BERYLLIUM ALLOYS				
Beryllium Copper[8] sheet, flexure, condition AT, (178 ksi UTS), R=-1	45000, 2×10^7 (RT)	135000, 1.2×10^4 (RT)	110000, 10^6 (20°K)	150000, 1.2×10^5 (20°K)
Beryllium Copper[8] sheet, flexure, condition 1/2 hard, (191 ksi UTS), R=-1	50000, 10^7 (RT)	105000, 2×10^4 (RT)	90000, 10^6 (20°K)	160000, 2×10^4 (20°K)

Table 4.43 Fatigue Strength in PSI of Copper and Copper Alloys and Corresponding Life Cycles

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
COPPER-ZINC ALLOYS (BRASS)				
70/30 Brass[8], sheet, flexure, cold rolled, stress relieved, R=1, (k_t=3.2)	20000, 7×10^6 (RT)	75000, 7×10^3 (RT)	50000, 10^6 (20°K)	100000, 3×10^4 (20°K)
70/30 Brass[8], sheet, flexure, cold rolled, stress relieved, R=1, (k_t=6.4)	20000, 3×10^6 (RT)	65000, 10^4 (RT)	50000, 10^6 (20°K)	95000, 4×10^4 (20°K)
COPPER-BERYLLIUM ALLOYS				
Beryllium Copper[8], sheet, flexure, condition AT, (170 ksi UTS), R=-1, (k_t=3.2)	20000, 1.2×10^7 (RT)	105000, 8×10^3 (RT)	45000, 1.2×10^6 (20°K)	105000, 4×10^4 (20°K)
Beryllium Copper[8], sheet, flexure, condition 1/2 hard, (191 ksi UTS), R=-1, (k_t=3.1)	27000, 10^7 (RT)	80000, 4×10^3 (RT)	50000, 10^6 (20°K)	85000, 1.2×10^4 (20°K)

Table 4.44 Notch Fatigue Strength in PSI of Copper and Copper Alloys and Corresponding Life Cycles

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
Beryllium Copper[8], sheet, flexure, condition 1/2 hard, (191 ksi UTS), R=-1, (k_t=6.6)	25000, 4×10^6 (RT)	80000, 2×10^3 (RT)	30000, 10^6 (20°K)	85000, 6×10^4 (20°K)

Table 4.44 Notch Fatigue Strength in PSI of Copper and Copper Alloys and Corresponding Life Cycles (cont.)

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
Pure Nickel A[8], sheet, flexure, annealed, R=-1	40000, 3×10^6 (RT)	85000, 9×10^4 (RT)	80000, 10^6 (20°K)	135000, 6×10^4 (20°K)
Hastelloy C[8], sheet, axial, soln treated, R=-1	45000, 4×10^6 (RT)	80000, 6×10^2 (RT)	90000, 2×10^6 (20°K)	113000, 4×10^2 (20°K)
Inconel[8], sheet, flexure, cold rolled, (132 ksi UTS), R=-1	45000, 10^7 (RT)	155000, 10^4 (RT)	100000, 8×10^5 (20°K)	180000, 2.5×10^4 (20°K)
Inconel X[8], sheet, flexure, soln treated, aged, R=-1	60000, 10^6 (RT)	185000, 6×10^3 (RT)	110000, 10^6 (20°K)	175000, 4×10^4 (20°K)
Inconel-718[8], sheet, axial, soln treated, R=-1	72000, 2×10^6 (RT)	98000, 3×10^2 (RT)	100000, 3×10^6 (20°K)	112000, 8×10^2 (20°K)
K-Monel[8], sheet, flexure, cold rolled, 1/2 hard, aged (182 ksi UTS), R=-1	35000, 1.2×10^7 (RT)	120000, 2×10^4 (RT)	100000, 10^6 (20°K)	150000, 4×10^4 (20°K)

Table 4.45 Fatigue Strength in PSI of Nickel and Nickel Alloys and Corresponding Life Cycles

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
Pure Nickel A[8], sheet, flexure, annealed, R=-1, (k_t=3.2)	15000, 1.2 x 10^7 (RT)	30000, 2 x 10^3 (RT)	35000, 1.1 x 10^6 (20°K)	50000, 4 x 10^3 (20°K)
Hastelloy C[8], sheet, axial, soln treated, R=-1, (k_t=3.8)	15000, 2 x 10^6 (RT)	70000, 2 x 10^3 (RT)	12000, 4 x 10^6 (20°K)	92000, 2 x 10^3 (20°K)
Inconel[8], sheet, flexure, cold rolled, (1132 ksi UTS) R=-1, (k_t=3.2)	30000, 7 x 10^6 (RT)	115000, 8 x 10^3 (RT)	50000, 10^6 (20°K)	120000, 5 x 10^4 (20°K)
Inconel X[8], sheet, flexure, soln treated, aged, R=-1, (k_t=3.2)	55000, 10^7 (RT)	100000, 4 x 10^4 (RT)	70000, 10^6 (20°K)	130000, 2 x 10^4 (20°K)
Inconel 718[8], sheet, axial, soln treated, R=-1, (k_t=3.5)	35000, 2.2 x 10^6 (RT)	79000, 1.5 x 10^3 (RT)	32000, 2 x 10^6 (20°K)	98000, 4 x 10^3 (20°K)
K-Monel[8], sheet flexure, cold rolled, 1/2 hard, aged, (182 ksi UTS) R=-1, (k_t=3.2)	10000, 10^7 (RT)	85000, 10^4 (RT)	30000, 1.5 x 10^6 (20°K)	100000, 4 x 10^4 (20°K)

Table 4.46 Notch Fatigue Strength in PSI of Nickel and Nickel Alloys and Corresponding Life Cycles

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
Narmco 513 Resin[8], 181 glass cloth reinforced, axial, R=.05	12000, 10^6 (RT)	28000, 10^3 (RT)	23000, 4×10^5 (77.6°K)	57000, 4×10^2 (77.6°K)
Trevarno F130 Resin[8], 181 glass cloth reinforced, axial, R=.05	11000, 10^6	21000, 2×10^3	24000, 10^6	52000, 4×10^2

Table 4.46 Fatigue Strength in PSI of Composite Materials and Corresponding Life Cycles (cont.)

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
CONSTRUCTION STEELS				
AISI/SAE 1075[8], sheet, flexure, hardened, tempered, R=-1	50000, 10^7 (RT)	240000, 4×10^3 (RT)	105000, 10^6 (20°K)	190000, 7×10^3 (20°K)
2800 (9% Ni)[8], sheet, flexure, double normalized, stress relieved, (128 ksi UTS), R=-1	70000, 10^6 (RT)	130000, 2×10^4 (RT)	115000, 10^6 (20°K)	175000, 1.5×10^4 (20°K)
STAINLESS STEEL-AUSTENITIC				
AISI 321[8], sheet, axial, annealed, R=-1	30000, 2×10^6 (RT)	52000, 5×10^2 (RT)	50000, 2×10^6 (20°K)	125000, 8×10^2 (20°K)
AISI 347[8], sheet, flexure, annealed, R=-1	17000, 10^6 (RT)	95000, 2×10^4 (RT)	95000, 9×10^5 (20°K)	170000, 4×10^4 (20°K)
A-286[8], sheet, axial, soln treated, R=-1	35000, 3×10^6 (RT)	53000, 7×10^2 (RT)	64000, 2×10^6 (20°K)	92000, 6×10^2 (20°K)
17-7PH-TH1050[8], sheet, flexure, (196 ksi UTS), R=-1	85000, 10^7 (RT)	150000, 2×10^4 (RT)	110000, 10^6 (20°K)	155000, 10^4 (20°K)

Table 4.47 Fatigue Strength in PSI of Ferrous Materials and Corresponding Life Cycles

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
CONSTRUCTION STEELS				
AISI/SAE 1075[8], sheet, flexure, hardened, tempered, R=-1, (k_t=3.2)	30000, 10^6 (RT)	80000, 1.5×10^4 (RT)	30000, 10^6 (20°K)	60000, 2×10^3 (20°K)
2800 (9% Ni)[8], sheet, flexure, double normalized, stress relieved, (128 ksi UTS), R=-1, (k_t=3.1)	30000, 2×10^7 (RT)	80000, 2×10^4 (RT)	45000, 4×10^5 (20°K)	75000, 10^4 (20°K)
STAINLESS STEEL-AUSTENITIC				
AISI 301[8], sheet, flexure, extra full hard, (241 ksi UTS), R=-1, (k_t=3.1)	25000, 10^7 (RT)	95000, 3×10^4 (RT)	60000, 7×10^4 (20°K)	140000, 4×10^3 (20°K)
AISI 304[8], bar, flexure, cold reduced, (212 ksi UTS), R=-1, (k_t=2.75)	20000, 10^7 (RT)	130000, 5×10^3 (RT)	55000, 10^6 (20°K)	60000, 4×10^4 (20°K)
AISI 321[8], sheet, axial, annealed, R=-1, (k_t=3.5)	15000, 1.5×10^6 (RT)	42000, 7×10^2 (RT)	27000, 1.5×10^6 (20°K)	90000, 6×10^2 (20°K)

Table 4.48 Notch Fatigue Strength in PSI of Ferrous Materials and Corresponding Life Cycles

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
AISI 347[8], sheet, flexure, annealed, R=-1, (k_t=3.2)	25000, 8 x 10^6 (RT)	52000, 10^4 (RT)	70000, 10^6 (20°K)	95000, 3 x 10^4 (20°K)
A-286[8], sheet, axial, soln treated, R=-1, (k_t=3.5)	21000, 3 x 10^6 (RT)	50000, 6 x 10^2 (RT)	16000, 2 x 10^6 (20°K)	90000, 2 x 10^3 (20°K)

Table 4.48 Notch Fatigue Strength in PSI of Ferrous Materials and Corresponding Life Cycles (cont.)

MATERIAL	Low F_n, n (uppper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
TITANIUM-ALPHA				
Ti-5Al-2.5Sn[8], sheet, axial, low interstitial, annealed, (116 ksi UTS), R=.01	75000, 10^6 (RT)	125000, 6×10^2 (RT)	130000, 6×10^6 (20°K)	225000, 2×10^2 (20°K)
TITANIUM-ALPHA-BETA				
Ti-6Al-4V[8], sheet, flexure, annealed, (136 ksi UTS), R=-1	45000, 10^7 (RT)	115000, 6×10^3 (RT)	80000, 10^6 (20°K)	145000, 2×10^4 (20°K)
Ti-6Al-4V[8], sheet, axial, low interstitial, soln treated, aged, (165 ksi UTS), R=-1	70000, 5×10^6 (RT)	170000, 3×10^3 (RT)	130000, 9×10^5 (20°K)	190000, 10^4 (20°K)
TITANIUM-BETA				
Ti-13V-11Cr-3Al[8], sheet, axial, soln treated, aged, (200 ksi UTS), R=.01	80000, 6×10^6 (RT)	185000, 6×10^3 (RT)	105000, 3×10^6 (20°K)	180000, 1.5×10^3 (20°K)

Table 4.49 Fatigue Strength in PSI of Titanium Alloys and Other Metals and Corresponding Life Cycles

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
OTHER METALS				
Ni-SPAN-C[8], sheet, flexure, soln treated, aged, (152 ksi UTS), R=-1	65000, 10^7 (RT)	115000, 1.5×10^4 (RT)	130000, 10^6 (20°K)	150000, 6×10^4 (20°K)

Table 4.49 Fatigue Strength in PSI of Titanium Alloys and Other Metals and Corresponding Life Cycles (cont.)

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
TITANIUM-ALPHA-BETA				
Ti-6Al-4V[8], sheet, flexure, annealed, (136 ksi UTS), R=-1, (k_t=3.1)	25000, 1.1 x 10^6 (RT)	70000, 1.5 x 10^4 (RT)	35000, 10^6 (20°K)	100000, 10^4 (20°K)
Ti-6Al-4V[8], sheet, flexure, annealed, (136 ksi UTS), R=-1, (k_t=6.4)	20000, 3 x 10^6 (RT)	75000, 10^4 (RT)	30000, 10^6 (20°K)	80000, 3 x 10^4 (20°K)
OTHER METALS				
Ni-SPAN-C[8], sheet, flexure, soln treated, aged, (152 ksi UTS), R=-1, (k_t=3.1)	25000, 6 x 10^6 (RT)	100000, 2 x 10^4 (RT)	65000, 6 x 10^5 (20°K)	145000, 2 x 10^4 (20°K)

Table 4.50 Notch Fatigue Strength in PSI of Titanium Alloys and Other Metals and Corresponding Life Cycles

MATERIAL	Low F_n, n (upper temp)	High F_n, n (upper temp)	Low F_n, n (lowest temp)	High F_n, n (lowest temp)
Epon 828 Resin[8], 181 glass cloth reinforced, axial, R=.05	22000, 1.5×10^6 (RT)	35000, 4×10^3 (RT)	35000, 10^6 (20°K)	79000, 10^4 (20°K)
Narmco 506 Resin[8], 181 glass cloth reinforced, axial, R=.05	15000, 10^6 (RT)	33000, 10^3 (RT)	22000, 10^6 (20°K)	54000, 10^2 (20°K)
CTL 91LD Resin[8], 181 glass cloth reinforced, axial, R=.05	22000, 10^6 (RT)	47000, 3×10^2 (RT)	32000, 10^6 (20°K)	58000, 3×10^2 (20°K)
Paraplex P43 Resin[8], 181 glass cloth reinforced, axial, R=.05	13000, 4×10^5 (RT)	40000, 2×10^2 (RT)	24000, 5×10^5 (20°K)	48000, 6×10^2 (20°K)
Vibrin 135 Resin[8], 181 glass cloth reinforced, axial, R=.05	24000, 1.5×10^6 (RT)	40000, 1.5×10^3 (RT)	33000, 10^6 (20°K)	52000, 6×10^2 (20°K)
Laminac 4231 Resin[8], 181 glass cloth reinforced, axial, R=.05	12000, 10^6 (RT)	38000, 2×10^2 (RT)	22000, 10^6 (20°K)	42000, 4×10^2 (20°K)

Table 4.51 Fatigue Strength in PSI of Composite Materials and Corresponding Life Cycles

MATERIAL	ENDURANCE LIMIT (upper temp)	ENDURANCE LIMIT (lowest temp)
5054-H32[23], bar, axial, R=0	28000 (RT)	36000 (77.6°K)
5083-H113[23], bar, axial, R=0	35000 (RT)	40000 (77.6°K)
5086-H32[23], bar, axial, R=0	34000 (RT)	40000 (77.6°K)
5456-H321[23], bar, axial, R=0	35000 (RT)	40000 (77.6°K)

Table 4.52 Endurance Limit of Aluminum Alloys in PSI

MATERIAL	k (upper temp)		k (lowest temp)	
1100-0[8]	122	(RT)	27	(4.2°K)
1100-F[8,9]	121	(RT)	28.5	(4.2°K)
2014-T6[8]	94	(RT)	28	(20°K)
2024-T4[8,9]	64	(205°K)	1.5	(4.2°K)
2219-T87[8]	68	(RT)	25	(47°K)
3003-F[8,9]	88.5	(116°K)	1.5	(4.2°K)
5052-0[8,9,13]	77	(211°K)	2.8	(4.2°K)
5083-0[8]	39	(122°K)	3	(4.2°K)
5086-F[8]	41	(122°K)	3	(4.2°K)
5154-0[8,9,13]	72	(122°K)	2.1	(4.2°K)
6063-T5[9,13]	117.8	(RT)	20.4	(4.2°K)
7039-T61[8,13]	87	(RT)	3.09	(4.2°K)
7075-T6[8]	73	(RT)	11	(4.2°K)

Table 4.53 Thermal Conductivity of Aluminum and Aluminum Alloys in BTU/HR-FT-°F

MATERIAL	k (upper temp)		k (lowest temp)	
PURE COPPER				
ETP Copper[9]	240	(RT)	180	(4.2°K)
OFHC Copper[8]	220	(RT)	575	(20°K)
99.999% Pure Copper[8]	0.2	(RT)	6	(4.2°K)
COPPER-ZINC ALLOYS (BRASSES)				
98 Cu, 2 Zn[13]	150.3	(100°K)	28.9	(10°K)
95 Cu, 5 Zn[13]	98.3	(95°K)	17.3	(10°K)
Alpha Brass[13] 68Cu,32Zn	31.8	(90°K)	2.3	(4.2°K)
Leaded Brass[13] 60.03Cu,35.7Zn, 3.27Pb,1Sn	30	(120°K)	1.27	(4.2°K)
Silber Bronze[13] 46Cu,41Zn,13Ni	31.2	(20°K)	.64	(4.2°K)
COPPER-TIN ALLOYS (BRONZES)				
Phosphor Bronze[13] 93.3Cu,6.46Sn,.3P	14.5	(80°K)	0.98	(4.2°K)
COPPER-SILICON ALLOYS				
Silicon Bronze[13]	7.5	(90°K)	1.4	(17°K)
COPPER-NICKEL ALLOYS				
Constantan[13] 55Cu,45Ni	13.3	(RT)	5.5	(25°K)
MISCELLANEOUS COPPER ALLOYS				
95.5 Cu, 4.5 Au[13]	50	(95°K)	14	(20°K)
90.3 Cu, 9.7 Au[13]	26.6	(100°K)	13.9	(20°K)

Table 4.54 Thermal Conductivity of Copper and Copper Alloys in BTU/HR-FT-°F

MATERIAL	k (upper temp)	k (lowest temp)
98.94 Cu, 1.04 Pb[13]	242.8 (80°K)	161.9 (6°K)
Manganin[13] 85Cu,12Mn,3Ni	7.2 (80°K)	0.35 (5°K)

Table 4.54 Thermal Conductivity of Copper and Copper Alloys in BTU/HR-FT-°F (cont.)

MATERIAL	k (upper temp)	k (lowest temp)
PURE NICKEL		
99.999% Pure Nickel[8,9] annealed	50 (RT)	100 (4.2°K)
NICKEL ALLOYS		
Monel[9], annealed hot rolled	12 (RT)	0.52 (4.2°K)
Monel[9], hard drawn, cold rolled	12 (RT)	0.31 (4.2°K)
Inconel[8,9], annealed	9 (RT)	0.65 (4.2°K)
Inconel[9] hard drawn	5.5 (80°K)	0.17 (4.2°K)
Inconel X[8] soln treated, double aged	6.8 (RT)	0.1 (4.2°K)
Inconel 718[8]	6.3 (RT)	0.4 (4.2°K)
Hastelloy X[8]	6.4 (RT)	0.4 (4.2°K)

Table 4.55 Thermal Conductivity of Nickel and Nickel Alloys in BTU/HR-FT-°F

MATERIAL	k (upper temp)		k (lowest temp)	
IRON				
99.999% Pure Iron[9]	47	(RT)	42	(4.2°K)
CONSTRUCTION STEELS				
SAE 1020[13]	.038	(RT)	0.016	(26°K)
SAE 1095[16]	.1	(RT)	0.02	(20°K)
STAINLESS STEEL-MARTENSITIC				
AISI 410[8]	16	(RT)	2.5	(20°K)
STAINLESS STEEL-AUSTENITIC				
AISI 303[8]	5	(77.6°K)	0.25	(4.2°K)
AISI 304[8]	9	(RT)	0.2	(4.2°K)
AISI 347[8]	8.5	(RT)	0.2	(4.2°K)

Table 4.56 Thermal Conductivity of Ferrous Materials in BTU/HR-FT-°F

MATERIAL	k (upper temp)	k (lowest temp)
TITANIUM-ALPHA		
Ti-5Al-2.5Sn[8]	4.7 (RT)	0.4 (4.2°K)
99.99% Pure Ti[8]	13 (RT)	4 (4.2°K)
TITANIUM-ALPHA BETA		
Ti-6Al-4V[8]	4.3 (RT)	0.7 (20°K)

Table 4.57 Thermal Conductivity of Titanium and Titanium Alloys in BTU/HR-FT-°F

MATERIAL	k (upper temp)	k (lowest temp)
99.99% Pure Silver[9] annealed	240 (RT)	8000 (4.2°K)
99.99% Pure Gold[9] annealed	190 (RT)	960 (4.2°K)
98% Pure Zirconium	24 (40°K)	7 (4.2°K)
99.98% Pure Tantalum	35 (100°K)	8.7 (4.2°K)

Table 4.58 Thermal Conductivity of Miscellaneous Metals in BTU/HR-FT-°F

MATERIAL	k (upper temp)	k (lowest temp)
Epoxy Fiberglass[8] Laminate E787 Resin, S/901 glass roving	0.42 (RT)	0.05 (20°K)
Epoxy Fiberglass Laminate EPON 828 Resin, S/901 glass roving	0.1 (RT)	0.02 (20°K)

Table 4.59 Thermal Conductivity of Composite Materials in BTU/HR-FT-°F

MATERIAL	k (upper temp)		k (lowest temp)	
Teflon[9], extruded	0.14	(80°K)	0.03	(4.2°K)
Nylon[9], drawn, monofilament	0.055	(20°K)	0.007	(4.2°K)
Perspex[9], organic glass thermo-plastic	0.05	(24°K)	0.035	(4.2°K)
Mylar[8], 0.014 inch sheet	0.6	(RT)	0.3	(20°K)
Plexiglas[13]	0.0491	(72°K)	0.0329	(4.2°K)
Polyethylene[13]	0.0346	(10°K)	0.0104	(4.2°K)

Table 4.60 Thermal Conductivity of Polymers in BTU/HR-FT-°F

MATERIAL	k (upper temp)	k (lowest temp)
Glass - average of quartz, pyrex and borosilicate glasses	0.56 (RT)	0.06 (4.2°K)

Table 4.61 Thermal Conductivity of Glass in BTU/HR-FT-°F

MATERIAL	c_p (upper temp)	c_p (lowest temp)
Pure Aluminum[9,12]	0.2125 (RT)	0.065 (4.2°K)
Pure Copper[9,12]	0.0837 (RT)	0.022 (4.2°K)
Pure Nickel[9,12]	0.1055 (RT)	0.0012 (4.2°K)
Monel[12]	0.1029 (RT)	0.0014 (20°K)
α-Iron[9,12]	0.1035 (RT)	0.000095 (4.2°K)
γ-Iron[9,12]	0.118 (RT)	0.0012 (20°K)
18-8 Stainless Steel[12], 74 γ-iron, 18 Cr, 8 Ni	0.114 (RT)	0.0011 (20°K)
Pure Titanium[9]	0.11 (RT)	0.00008 (4.2°K)
Pure Magnesium[12]	0.235 (RT)	0.004 (20°K)
Pure Chromium[12]	0.1073 (RT)	0.0006 (20°K)
Teflon-Molded[9]	0.22 (RT)	0.0001 (5°K)
Polyethylene[9]	0.54 (RT)	0.088 (60°K)

Table 4.62 Constant Pressure Specific Heat of Various Materials in BTU/LBM°F

MATERIAL	α (upper temp)	α (lowest temp)
Pure Aluminum[8]	0 (RT)	-0.00415 (4.2°K)
1100-0[8]	0 (RT)	-0.00405 (20°K)
2014-T6[8]	0 (RT)	-0.0042 (20°K)
2020-T6[8]	0 (RT)	-0.0041 (20°K)
2024-T86[8]	0 (RT)	-0.0042 (20°K)
2219-T87[8]	0 (RT)	-0.0042 (20°K)
5456-H343[8]	0 (RT)	-0.0043 (20°K)
6061-T6[8]	0 (RT)	-0.00415 (20°K)
7039-T6[8]	0 (RT)	-0.0042 (20°K)
7075-T6[8]	0 (RT)	-0.0042 (20°K)
356-T6[8], permanent mold casting	0 (RT)	-0.0039 (20°K)
TENS-50[8]	0 (RT)	-0.0039 (20°K)

Table 4.63 Linear Thermal Expansion Coefficient of Aluminum and Aluminum Alloys in Inches per Inch

MATERIAL	α (upper temp)		α (lowest temp)	
Pure Copper[9]	0	(RT)	-0.00327	(4.2°)
Pure Copper[8] annealed	0	(RT)	-0.00325	(20°K)
70/30 Brass[8] 3/4 hard	0	(RT)	-0.00375	(20°K)
Yellow Brass[12] free machining	0.00397	(RT)	0	(0°K)
Beryllium Copper[8]	0	(RT)	-0.0031	(20°K)

Table 4.64 Linear Thermal Expansion Coefficient of Copper and Copper Alloys in Inches per Inch

MATERIAL	α (upper temp)	α (lowest temp)
Pure Nickel[9]	0 (RT)	-0.00225 (4.2°K)
Pure Nickel[8], annealed	0 (RT)	-0.0023 (20°K)
Monel[12]	0.00261 (RT)	0 (0°K)
Inconel[13]	0.00238 (RT)	0 (0°K)
Inconel[8], annealed	0 (RT)	-0.0023 (20°K)
Inconel X[8] soln treated, aged	0 (RT)	-0.0025 (20°K)
Inconel 718[8]	0 (RT)	-0.00235 (20°K)
K-Monel[8], soln treated, aged	0 (RT)	-0.0025 (20°K)
S-Monel[8], annealed	0 (RT)	-0.0025 (20°K)
Hastelloy B[8], annealed	0 (RT)	-0.0019 (20°K)
Rene 41[8], soln treated	0 (RT)	-0.0022 (20°K)
D-979[8], annealed	0 (RT)	-0.00235 (20°K)
L-605[8]	0 (RT)	-0.00215 (20°K)

Table 4.65 Linear Thermal Expansion Coefficient of Nickel and Nickel Alloys in Inches per Inch

MATERIAL	α (upper temp)	α (lowest temp)
IRON		
Iron[9]	0 (RT)	-0.00198 (4.2°K)
CONSTRUCTION STEELS		
SAE 1020[12]	0.0021 (RT)	0 (0°K)
SAE 1075[8] quenched and tempered	0 (RT)	-0.00195 (20°K)
SAE 4340[8], annealed	0 (RT)	-0.00193 (20°K)
9% Nickel Steel[8] double normalized and tempered	0 (RT)	-0.0021 (20°K)
9% Nickel Steel[11] double normalized and stress relieved	0 (RT)	-0.0019 (4.2°K)
STAINLESS STEELS-MARTENSITIC		
AISI 410[8]	0 (RT)	-0.00175 (20°K)
AISI 416[8]	0 (RT)	-0.0018 (20°K)
AISI 440C[8]	0 (RT)	-0.0018 (20°K)
17-4PH-H1100[8]	0 (RT)	-0.0019 (20°K)
STAINLESS STEELS-AUSTENITIC		
AISI 302[8,11], cold drawn	0 (RT)	-0.0031 (20°K)
AISI 303[8], annealed	0 (RT)	-0.003 (20°K)
AISI 304[12]	0.00304 (RT)	0 (0°K)

Table 4.66 Linear Thermal Expansion Coefficient of Ferrous Materials in Inches per Inch

MATERIAL	α (upper temp)	α (lowest temp)
AISI 304[8,11] annealed	0 (RT)	-0.003 (20°K)
AISI 310[8], annealed	0 (RT)	-0.00285 (20°K)
AISI 321[8], annealed	0 (RT)	-.0029 (20°K)
AISI 347[8], annealed	0 (RT)	-0.003 (20°K)
A-286[8], soln treated, aged	0 (RT)	-0.0029 (20°K)
17-7PH-TH1050[8]	0 (RT)	-0.00225 (20°K)

Table 4.66 Linear Thermal Expansion Coefficient of Ferrous Materials in Inches per Inch (cont.)

MATERIAL	α (upper temp)		α (lowest temp)	
TITANIUM-ALPHA				
Ti-5Al-2.5Sn[8] normal interstitial, annealed	0	(RT)	-0.00175	(20°K)
Ti-8Al-1Mo-1V[8] annealed	0	(RT)	-0.0016	(20°K)
Pure Titanium[12]	0.00155	(RT)	0	(0°K)
TITANIUM-ALPHA-BETA				
Ti-6Al-4V[8], normal interstitial, annealed	0	(RT)	-0.0017	(20°K)
TITANIUM-BETA				
Ti-13V-11Cr-3Al[8], soln treated	0	(RT)	-0.0016	(20°K)

Table 4.67 Linear Thermal Expansion Coefficient of Titanium and Titanium Alloys in Inches per Inch

MATERIAL	α (upper temp)	α (lowest temp)
Pure Silver[7]	0 (RT)	-0.00413 (4.2°K)
Elgiloy[8], 45% cold reduction	0 (RT)	-0.00255 (20°K)
Ni-SPAN-C[8], soln treated, aged	0 (RT)	-0.0013 (20°K)
Pure Magnesium[12]	0.00503 (RT)	0 (0°K)
Pure Zinc[12]	0.00572 (RT)	0 (0°K)

Table 4.68 Linear Thermal Expansion Coefficient of Miscellaneous Metals in Inches per Inch

MATERIAL	α (upper temp)	α (lowest temp)
TFE Teflon, 65% bronze filled[8]	0 (RT)	-0.0145 (20°K)
TFE Teflon, 15% graphite filled[8]	0 (RT)	-0.0155 (20°K)
TFE Teflon, 25% asbestos filled[8]	0 (RT)	-0.0205 (20°K)
FEP Teflon, 20% glass filled[8]	0 (RT)	-0.009 (20°K)
TFE Teflon, 25% glass filled[8]	0 (RT)	-0.016 (20°K)
FEP Teflon, 116 glass cloth reinforced, with fabric[8]	0 (RT)	-0.0037 (20°K)
TFE Teflon, 128 glass cloth reinforced, with fabric[8]	0 (RT)	-0.0042 (20°K)
TFE Teflon, 128 glass cloth reinforced, through fabric[8]	0 (RT)	-0.0135 (20°K)
TFE Molded Teflon, chopped glass fibers, random orientation, normal to thickness[8]	0 (RT)	-0.065 (20°K)
TFE Molded Teflon, chopped glass fibers, random orientation, with thickness[8]	0 (RT)	-0.025 (20°K)
TFE Molded Teflon, 0.5 inch squares of graphite cloth, random orientation, normal to thickness[8]	0 (RT)	-0.08 (20°K)
TFE Molded Teflon, 0.5 inch squares of graphite cloth, random orientation, with thickness[8]	0 (RT)	-0.02 (20°K)
TFE Teflon, long fiber felted asbestos, sheet reinforced, with warp[8]	0 (RT)	-0.002 (20°K)
TFE Teflon, long fiber felted asbestos, sheet reinforced, with weave[8]	0 (RT)	-0.0035 (20°K)

Table 4.69 Linear Thermal Expansion Coefficient of Composite Materials in Inches per Inch

MATERIAL	α (upper temp)	α (lowest temp)
TFE Teflon, long fiber felted asbestos,[8] sheet reinforced, with thickness	0 (RT)	-0.03 (20°K)
E-787 Resin, S/901 roving bidirectional filament[8] reinforced, parallel to reinf.	0 (RT)	-0.0016 (20°K)
E-787 Resin, S/901 roving bidirectional filament[8] reinforced, perpendicular to reinf.	0 (RT)	-0.00145 (20°K)
E-787 Resin, S/901 roving unidirectional filament[8] reinforced, parallel to reinf.	0 (RT)	-0.0007 (20°K)
E-787 Resin, S/901 roving unidirectional filament[8] reinforced, perpendicular to reinf.	0 (RT)	-0.0056 (20°K)
E-787 Resin, S/901 1543 cloth reinforced[8] parallel to reinf.	0 (RT)	-0.0012 (20°K)
E-787 Resin, S/901 1543 cloth reinforced[8] perpendicular to reinf.	0 (RT)	-0.0041 (20°K)
E-787 Resin, S/901 1581 cloth reinforced[8] parallel to reinf.	0 (RT)	-0.0023 (20°K)
E-787 Resin, S/901 1581 cloth reinforced[8] perpendicular to reinf.	0 (RT)	-0.0025 (20°K)
E-787 Resin, S-994/HTS unidirectional filament[8] glass roving, normal to thickness	0 (RT)	-0.0007 (20°K)

Table 4.69 Linear Thermal Expansion Coefficient of Composite Materials in Inches per Inch (cont.)

MATERIAL	α (upper temp)	α (lowest temp)
E-787 Resin, S-994/HTS unidirectional filament[8] glass roving, with thickness	0 (RT)	-0.0034 (20°K)
Epon 828 Resin, potassium titanate fiber[8] random orientation, normal to thickness	0 (RT)	-0.0042 (20°K)
Epon 828 Resin, potassium titanate fiber[8] random orientation, with thickness	0 (RT)	-0.0077 (20°K)
Epon 828 Resin, phenolic micro-balloons (BJ00930),[8] random orientation, normal to thickness	0 (RT)	-0.0085 (20°K)
Epon 828 Resin, phenolic micro-balloons (BJ00930),[8] random orientation, with thickness	0 (RT)	-0.0088 (20°K)
Epon 828 Resin, perlite granules (LM-30),[8] random orientation, normal to thickness	0 (RT)	-0.003 (20°K)
Epon 828 Resin, perlite granules (LM-30),[8] random orientation, with thickness	0 (RT)	-0.003 (20°K)
Epon 828 Resin, glass micro-balloons (eccospheres R),[8] normal to thickness	0 (RT)	-0.0046 (20°K)
Epon 828 Resin, glass micro-balloons (eccospheres R)[8] with thickness	0 (RT)	-0.0049 (20°K)
CTL-91LD Resin, E/VOLAN A, 181 glass cloth reinforced[8] with warp	0 (RT)	-0.0015 (20°K)
CTL-91LD Resin, E/VOLAN A, 181 glass cloth reinforced[8] with weave	0 (RT)	-0.0016 (20°K)

Table 4.69 Linear Thermal Expansion Coefficient of Composite Materials in Inches per Inch (cont.)

MATERIAL	α (upper temp)	α (lowest temp)
CTL-91LD Resin, E/VOLAN A, 181 glass cloth reinforced[8] with thickness	0 (RT)	-0.0041 (20°K)
SC-1008 Resin, WCB graphite cloth reinforced[8] with warp	0 (RT)	-0.001 (20°K)
SC-1008 Resin, WCB graphite cloth reinforced[8] with weave	0 (RT)	-0.0014 (20'K)
SC-1008 Resin, WCB graphite cloth reinforced[8] with thickness	0 (RT)	-0.0042 (20°K)
CTL-91LD Resin, SN-19 Nylon-YN-25 cloth in 0.5 inch[8] squares, random orientation, normal to thickness	0 (RT)	-0.0083 (20°K)
CTL-91LD Resin, SN-19 Nylon-YN-25 cloth in 0.5 inch[8] squares, random orientation, with thickness	0 (RT)	-0.017 (20°K)
Selectron 5158 Resin, S/901 roving bidirectional[8] filament, parallel to reinf.	0 (RT)	-0.0011 (20°K)
Selectron 5158 Resin, S/901 roving bidirectional[8] filament, perpendicular to reinf.	0 (RT)	-0.0012 (20°K)
Paraplex P-43/Benzoyl Peroxide Styrene Resin[8] E/VOLAN A, 181 glass cloth, with warp	0 (RT)	-0.0028 (20°K)
Paraplex P-43/Benzoyl Peroxide Styrene Resin[8] E/VOLAN A, 181 glass cloth, with weave	0 (RT)	-0.003 (20°K)

Table 4.69 Linear Thermal Expansion Coefficient of Composite Materials in Inches per Inch (cont.)

MATERIAL	α (upper temp)	α (lowest temp)
Paraplex P-43/Benzoyl Peroxide Styrene Resin[8] E/VOLAN A, 181 glass cloth, with thickness	0 (RT)	-0.0086 (20°K)
DC-2106/XY-15 Resin, E/140 HTS glass roving[8] normal to thickness	0 (RT)	-0.0014 (20°K)
DC-2106/XY-15 Resin, E/140 HTS glass roving[8] with thickness	0 (RT)	-0.0061 (20°K)
SC-1013 Resin, X-994/A-1100, 181 glass cloth[8] with warp	0 (RT)	-0.0012 (20°K)
SC-1013 Resin, X-994/A-1100, 181 glass cloth[8] with weave	0 (RT)	-0.0013 (20°K)
SC-1013 Resin, X-994/A-1100, 181 glass cloth[8] with thickness	0 (RT)	-0.0054 (20°K)
Molded Polyester Rod with Glass Fibers[12]	0.00291 (RT)	0 (0°K)

Table 4.69 Linear Thermal Expansion Coefficient of Composite Materials in Inches per Inch (cont.)

MATERIAL	α (upper temp)		α (lowest temp)	
Nylon, FM-1[8]	0	(RT)	-0.0139	(20°K)
Mylar[8]	0	(RT)	-0.007	(20°K)
FEP Teflon[8]	0	(RT)	-0.018	(20°K)
TFE Teflon[8]	0	(RT)	-0.0215	(20°K)
KEL-F[8]	0	(RT)	-0.011	(20°K)
Cast Phenolic Rod[12]	0.00889	(RT)	0	(0°K)
Nylon Rod[12]	0.01107	(RT)	0	(0°K)
Fluorothene[12]	0.01187	(RT)	0	(0°K)
Polystyrene[12]	0.01566	(RT)	0	(0°K)
Polyfluoroethylene[12]	0.02695	(RT)	0	(0°K)
Epon 828/DSA/1040/BDMA (100/115.9/20/1)[27]	0	(RT)	-0.015	(20°K)
Epon 828/DSA/BOHET/BDMA (100/134/26/1)[27]	0	(RT)	-0.016	(20°K)
Epon 826/Epon 871/L-100/MDCA (35/15/50/27.6)[27]	0	(RT)	-0.015	(20°K)
Epon 826/1040/Z-6077/DSA/BDMA (80/20/20/115.9/1)[27]	0	(RT)	-0.0162	(20°K)

Table 4.70 Linear Thermal Expansion Coefficient of Polymers in Inches per Inch

MATERIAL	ρ (upper temp)	ρ (lowest temp)
Pure Aluminum[10]	2.53×10^{-8} (RT)	1.695×10^{-10} (4.2°K)
1100-0[8]	1.27×10^{-8} (155.4°K)	2×10^{-9} (4.2°K)
2024-T4[8]	3.35×10^{-8} (49.8°K)	3.1×10^{-8} (4.2°K)
2024-T4[26]	4.35×10^{-8} (273°K)	1.742×10^{-8} (4.2°K)
2024-T6[26]	4×10^{-8} (273°K)	1.337×10^{-8} (4.2°K)
5052-0[8]	2.6×10^{-8} (99.8°K)	2×10^{-8} (4.2°K)
5083-0[26]	5.66×10^{-8} (273°K)	3.03×10^{-8} (4.2°K)
7039-0[26]	4.75×10^{-8} (273°K)	2.12×10^{-8} (4.2°K)

Table 4.71 Electrical Resistivity of Aluminum and Aluminum Alloys in Ohm-Meters

MATERIAL	ρ (upper temp)	ρ (lowest temp)
PURE COPPER		
Pure Copper[10]	1.55×10^{-8} (RT)	1.86×10^{-11} (4.2°K)
OFHC Copper[26]	1.559×10^{-8} (273°K)	1.6×10^{-10} (4.2°K)
COPPER-ZINC ALLOYS (BRASS)		
70/30 Brass[26]	6.65×10^{-8} (273°K)	4.22×10^{-8} (4.2°K)
Admiralty Brass[26]	6.93×10^{-8} (273°K)	4.56×10^{-8} (4.2°K)

Table 4.72 Electrical Resistivity of Copper and Copper Alloys in Ohm-Meters

MATERIAL	ρ (upper temp)	ρ (lowest temp)
Nickel[10]	6.14×10^{-8} (RT)	3.07×10^{-10} (4.2°K)
Hastelloy N[26]	1.206×10^{-6} (273°K)	1.201×10^{-6} (4.2°K)
Hastelloy X[26]	1.138×10^{-6} (273°K)	1.076×10^{-6} (4.2°K)
Inconel X[26], annealed	1.245×10^{-6} (273°K)	1.209×10^{-6} (4.2°K)
Inconel X[26], aged	1.229×10^{-6} (273°K)	1.176×10^{-6} (4.2°K)

Table 4.73 Electrical Resistivity of Nickel and Nickel Alloys in Ohm-Meters

MATERIAL	ρ (upper temp)	ρ (lowest temp)
PURE IRON		
Iron[10]	8.6×10^{-8} (RT)	5.59×10^{-10} (4.2°K)
STAINLESS STEEL-AUSTENITIC		
AISI 304L[26]	7.04×10^{-7} (273°K)	4.96×10^{-7} (4.2°K)
AISI 321[26]	7.39×10^{-7} (273°K)	5.36×10^{-7} (4.2°K)
17-7PH[26], annealed	1.015×10^{-6} (273°K)	9.68×10^{-7} (4.2°K)
17-7PH[26], precipitation hardened	7.09×10^{-7} (273°K)	5.75×10^{-7} (4.2°K)

Table 4.74 Electrical Resistivity of Ferrous Materials in Ohm-Meters

MATERIAL	ρ (upper temp)	ρ (lowest temp)
TITANIUM-ALPHA		
Titanium[10]	8×10^{-7} (RT)	8×10^{-8} (4.2°K)
TITANIUM-ALPHA-BETA		
Ti-6Al-4V[26]	1.675×10^{-6} (273°K)	1.469×10^{-6} (20°K)
TITANIUM-BETA		
Ti-13V-11Cr-3Al[26]	1.492×10^{-6} (273°K)	1.567×10^{-6} (4.2°K)
OTHER METALS		
Tantalum[10]	1.24×10^{-7} (RT)	2.48×10^{-9} (4.2°K)
Zirconium[10]	4.1×10^{-7} (RT)	1.64×10^{-8} (4.2°K)

Table 4.75 Electrical Resistivity of Titanium and Titanium Alloys and Other Metals in Ohm-Meters

MATERIAL	μ at 295°K	μ at 77°K	μ at 4.2°K
AISI 304[28]	1.25761×10^{-6}	1.25747×10^{-6}	NO DATA
AISI 304L[28]	1.25782×10^{-6}	1.25762×10^{-6}	NO DATA
AISI 310[28]	1.25668×10^{-6}	1.25678×10^{-6}	1.25802×10^{-6}
AISI 321[28]	1.25703×10^{-6}	1.25707×10^{-6}	1.25703×10^{-6}
Tenelon[28]	1.25666×10^{-6}	1.25666×10^{-6}	NO DATA

Table 4.76 Magnetic Permeability of Austenitic Stainless Steels in Webers Per Amp-Turn-Meter

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CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusion which can be drawn from this thesis is that the entire area of cryogenic properties of materials is a relatively wide open field of research. Despite the large amount of experimental data in Tables 4.1 through 4.76, there are many knowledge gaps which will ultimately need to be filled. Cryogenic properties of materials in the areas of magnetic behavior, torsional behavior, electrical resistivity, specific heat and density are largely unexplored. On the other hand tensile properties, thermal conductivity and thermal expansion have been well researched. Notch toughness is in a class all by itself since, despite the large amount of data which exists, there is no general agreement on how to interpret this data.

With the decline in government funded research and development money, particularly by NASA and the United States Air Force, and the reluctance of large corporations to divulge their expensive private research efforts, the generation and dissemination of new data on the cryogenic properties of materials may have decreased significantly. There will probably always be a small but steady flow of new data from university research laboratories and government laboratories in many countries, but not on the same scale as in the past. This situation places the onus on a design agency to:

(1) Keep a continuous watch for newly published cryogenic property data which may be useful.

(2) Develope an in-house capability, however crude, to experimentally obtain data which cannot be found in the literature.

This thesis is a large first step in consolidating the data on cryogenic properties of materials which exists today into a single volume. Follow-on work could be done in one of three areas:

(1) Extending the data already provided by examining the references not already covered. This would be a tedious process, however, and it is questionable if the extensive effort required to do this would justify the results since many of the unused references are not in English or are very short articles covering just one property of one material.

(2) Explore the data available on the fabricability of materials for use at cryogenic temperatures. For example, some data was found on the behavior of weld metals at cyrogenic temperatures, but was not included in this work. There is probably a substantial amount of literature available on this and other subjects related to fabrication of materials for low temperature use, and this might very well prove to be a useful effort.

(3) Develope inexpensive and simple to build and use testing apparatus to provide cryogenic property data where none is available now. There are a great many references in the literature on testing procedures and testing apparatus and these would provide a good starting point.

One last recommendation is considered appropriate to anyone who becomes involved in searching the literature on cryogenic properties of materials. The authors of many articles and papers have a strong tendency to make definitive statements regarding how a group of materials or a specific material behaves at cryogenic temperatures. They make statements such as, "Material X has excellent notch toughness at liquid helium temperatures." Invariably there is no data in the article to support these claims and when data is finally found from some other source, it is not obvious why material X has such good notch toughness. Often such articles were written by the manufacturer of the materials, by someone whose research was supported by the manufacturer, or by someone who is attempting to draw conclusions from insufficient experimental data. It is felt that relying solely on the data, which may itself be questionable, and drawing one's own conclusions is a much better approach than believing statements such as that made above.

APPENDIX A

NATIONAL BUREAU OF STANDARDS LITERATURE SEARCH ON CRYOGENIC PROPERTIES OF MATERIALS

The purpose of this appendix is to provide a ready reference list to someone interested in finding information on cryogenic properties of materials.

The source of these references is a bibliography of references prepared on 24 October, 1973, for the staff of the Cryogenic Laboratory at M.I.T. by the Cryogenic Data Center, Institute for Basic Standards, National Bureau of Standards in Boulder, Colorado. The original bibliography of references is maintained in the M.I.T. Cryogenic Laboratory and contains many more entries than are presented here. In addition, the original provides general information on the content of each reference along with data concerning where the reference may be obtained.

What is provided here is a condensed version of the original with those references in foreign languages, some older outdated material, and any material not directly related to electrical machinery design eliminated. The material is broken into four major groups of materials: Composites; Nickel, Titanium, Aluminum Alloys and other Selected Alloys: Polymers; Steels. Within each material group there is a further breakdown into specific material properties which follow the breakdown in the original bibliography and basically match the properties given in Chapter 2.

The references are listed alphabetically within each material property group. If there is no reference listed under a group, this implies that the original had no reference. Following each reference is a multi-digit code. This number is the National Bureau of Standards file number for that reference. Knowing this number allows the researcher to use the original copy of the bibliography of references or permits smooth communication and information retrieval from the Cryogenic Data Center in Boulder, Colorado (telephone number 303-499-1000, extension 3257).

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NONE

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NONE

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A.2.1 Cryogenic Properties of Nickel Alloys

A.2.1.1 Mechanical Properties of Nickel Alloys

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NONE

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